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THERMAL REGIME OF EARTH ROCK DAMS CONSTRUCTED IN THE FAR NORTH

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Thermal Regime of Earth-Rock Dams Constructed in the Far North

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THERMAL REGIME OF EARTH-ROCK DAMS CONSTRUCTED IN THE FAR NORTH

Extensive exploitation of the natural riches of the Far North and permafrost regions has resulted in intensive construction of hydraulic engineering structures, including earth dams.

The earth-rock dam predominates under Far North conditions; because it is the most efficient and economical type of dam for handling medium and high heads. Earth dams are already in use at the Vilyuysk and Ust'-Khantaysk hydroelectric power stations; they are 74.5 and 67.0 m high, respectively. Construction of the Kolymsk hydroelectric power station dam, 126 m high, has begun. Preparatory work is under way for construction of the Kureysk and Ust'-Botuobsk hydroelectric power stations.

Hydraulic engineering construction practice has required scientific mastery of many problems which have arisen in designing earth-fill high-head dams in the northern construction climate zone of the USSR.

One question whose solution is of primary importance for the development of economically efficient construction of earth dams and the technology for their exploitation involves predicting and controlling the thermal regime of earth-rock dams during construction and operation.

This report describes methods developed at VNIIG* to calculate the thermal regime of earth dams, along with data from field observations of such structures.

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* All-Union Order of Labor of the Red Banner Scientific Research Institute of Hydraulic Engineering imeni B. Ye. Vedeneyev.

Methods of Calculating Thermal Regime in Earth Dams

An earth-rock dam, with an earth water-confining element built on a permafrost foundation, constitutes an open thermodynamic system. The material and energy interrelationships with the environment disturb the thermodynamic equilibrium of the structure. This is accompanied by development of currents of thermal energy, water, gases, and water vapor in it. The intensity of these currents is affected largely by external environmental factors, including air temperature and water, precipitation in the form of rain and snow, solar radiation, wind, and atmospheric humidity. The physical-mechanical, filtration and thermophysical properties of the material composing the dam and of the rock in the foundation also exert a significant influence.

The thermal regime of earth-rock dams is difficult to study. The situation is considerably simplified if we consider the individual elements of the dam, keeping in mind the conditions existing at their boundaries.

In this report, particular emphasis is placed upon the lower supporting prism of the dam, made of riprap.

Complex processes of heat and mass transfer take place in the lower prism of the dam. Free convection occurs in the the pores of the fill, and moisture condenses on the cooled individual lumps of rock during the summer, forming dew and ice. Ice formations sublimate in winter, with air flowing from them into the atmosphere. Precipitation filters in and water is filtered through, with considerable inhomogeneity of the body of the dam as far as temperature and filtration are concerned.

The lower prism must be viewed as a heterogeneous multicomponent system. Among its basic components are the mineral skeleton, ice, water, and vapor-air mixture.

Heat transport in this system is accomplished by thermal conductivity, radiation, and convection, while mass is transferred by molecular and molar exchange in the gas and liquid.

A characteristic feature of the heat and mass transfer processes in the riprap forming the body of the lower prism is their interdependence) hence, heat and mass transfer constitute a single process. The specific nature of this process also consists in the fact that due to the considerable size of the joints, the temperatures of the mineral skeleton,

the vapor-air mixture moving around in the pores, and the water are all different. The filtration rates of the vapor-air mixture change from zero to several meters per second, so that both laminar and transient flow regimes can develop in the pores. The structure of the porous space in the fill is disordered. The distribution of the joints and pores by shapes and sizes is statistical.

Therefore, in a physical description of the lower prism, we shall use statistical characteristics which allow the currents in a small volume to be homogenized and to introduce into the theory of heat and mass transfer in this complicated system, concepts of temperature, mass, pressure, speed, permeability, and the like at a given point.

For the lower prism of an earth-rock dam, VNIIG produced a complete system of two-dimensional equations representing heat and mass transfer, and formulated the boundary, initial, and limiting conditions of the problem. This system includes equations for heat transfer in the mineral skeleton, in the vapor-air mixture, and in water; mass-transfer equations; equations for the movement of the vapor-air mixture and water, and equations to determine the moisture content of the loose fill. The equations were obtained on the basis of the laws of conservation of energy, momentum and mass, on the condition that the corresponding transfer coefficients could be determined experimentally.

This problem takes into account the transfer of heat by conduction and convection in inhomogeneous porous media, as well as mass transfer by evaporation, condensation, sublimation, and displacement of water by infiltration.

The solution to the problem formulated in this manner poses considerable difficulties.

Therefore, in the first stage of the investigations, a number of simplifications were introduced.

In particular, for a description of heat transfer in inhomogeneous fill, a system of equations was proposed in which free convective heat exchange in the pores of the fill was taken into account, together with the transfer of heat by convection, but mass transfer was disregarded.

This system has the following form:

$$C_M \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda \frac{\partial T}{\partial y}\right] + \alpha_v(\theta - T).$$

$$\frac{\partial \theta}{\partial \tau} - \frac{1}{m}\frac{\partial \psi}{\partial y}\frac{\partial \theta}{\partial x} - \frac{1}{m}\frac{\partial \psi}{\partial x}\frac{\partial \theta}{\partial y} = \frac{\alpha_v}{m C_B}(T - \theta).$$

$$\frac{\partial}{\partial x}\left[K_0 \frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_0 \frac{\partial \psi}{\partial y}\right] = -\frac{\partial}{\partial x}\left[\gamma \beta m \theta'\right].$$

$$K_0 = \frac{\mu}{K}.$$

where $T = T(x,y,\tau)$ is the temperature of the mineral skeleton;

$\theta = \theta(x,y,\tau)$ is the temperature of the air in the pores;

$\theta' = \theta'(x,y,\tau)$ is the difference in air temperature inside and outside the pores;

$\psi = \psi(x,y)$ is the current function;

$\lambda = \lambda(x,y)$ is the coefficient of thermal conductivity of the fill;

$C_M = C_M(x,y)$, $C_B = C_B(x,y)$ is the specific volume thermal capacity of the skeleton and the air;

$\alpha_v = \alpha_v(x,y)$ is the coefficient of volume heat exchange between the solid skeleton and the air inside the pores;

$m = m(y)$ is the porosity;

$K = K(x,y)$ is the coefficient of permeability;

μ is the coefficient of dynamic viscosity of the air;

γ is the density of the air;

β is the coefficient of volume expansion of the air;

x, y are the Cartesian coordinates, and

τ is the time.

The solution to this system of equations, supplemented by corresponding initial and boundary conditions, was obtained by the method of finite differences. It was used as an algorithm in computer calculations of the thermal regime of the lower prism and the adjacent elements of the earth-rock dam of the Vilyuysk Hydroelectric Power Station. The numerical values required for calculating the physical, mechanical, and thermophysical characteristics of the rock fill, were established either on the basis of the results of experimental studies conducted under laboratory and field conditions on specially constructed devices, or from data in the literature.

During the construction of the dam, its thermal regime was calculated for the period from November 1, 1967, to January 31, 1968. Figure 1 shows the calculated temperature field in the channel section of the dam on January 31, 1968, showing the temperature sensors installed in the lower prism of the dam and their readings on that date. A comparison of the results obtained by calculation and in the field shows good agreement. The maximum difference in temperature in the lower prism between the calculated and actual values is 4°C. Marked deviation of the calculated results from the actual data was limited to a small zone adjacent to the upper and middle parts of the lower slope of the dam. It was found that the central part of the lower slope is also subject to massive influx of air to the lower prism during autumn and winter.

The computational data obtained on intensive and deep cooling of the talik beneath the river bed in the foundation of the lower prism were also confirmed by the results of field observations.

Field Observations of the Thermal Regime of the Vilyuysk Hydroelectric Power Station Dam

The construction site is in an area where there is extensive permafrost, estimated to be 400 to 500 meters thick.

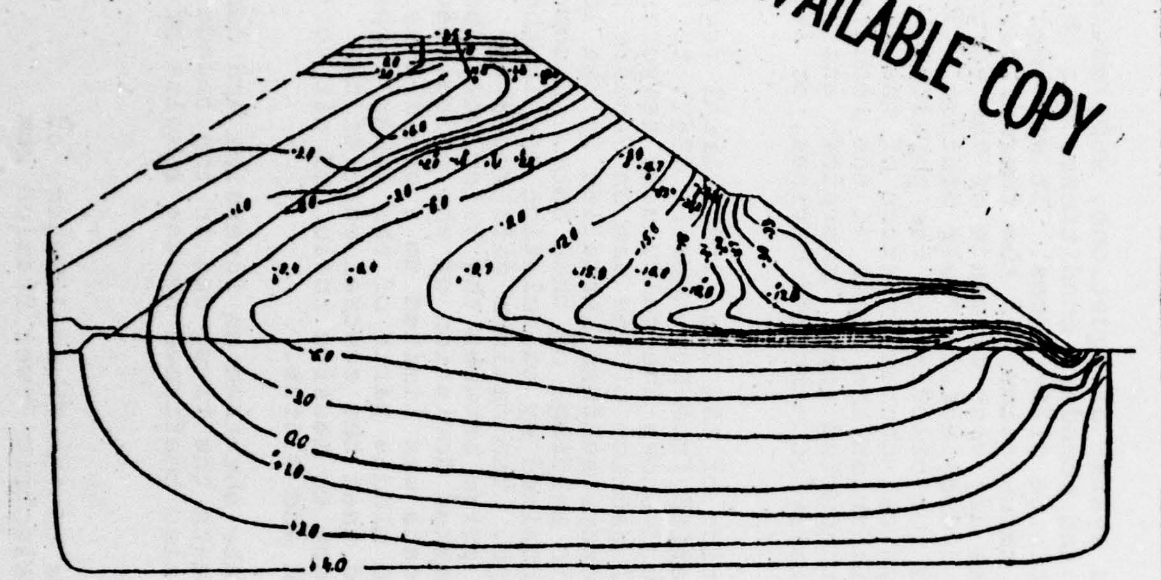

Figure 1. Calculated Temperature State of the Dam and Readings from Monitoring and Measuring Apparatus on January 31, 1968. 1-27: Locations of temperature sensors and their readings.

The average long-term air temperature is -8.2°C. The maximum air temperature was +36°C and the minimum was -63°C. The average long-term precipitation is 330 mm.

The dam foundation was built essentially of monolithic diabase. The rocks on the right bank were cooled to -6°C and those on the left to -2 to -3°C. The river bed contains a continuous talik, 110 to 130 m wide, whose preconstruction limits coincided with the low-water level.

The earth-rock dam, with a clay apron, has a maximum height of 74.5 m and a length of 600 m along the crest; the slope of the upper part varies from 1 to 1:5 at the top to 1:3 at the bottom. The lower slope was made with fine gravel, and the slope between the berms is 1:1.4.

The transition zone between the apron and lower prism is made of two layers of gravel (fractions 0-40 and 0-150 mm) and a stabilizing rock layer composed of stones up to 300 mm in diameter.

Temperature sensors were installed in the body and foundation of the dam when it was started, and are still being installed.

Observations have shown that natural air convection involves the entire lower prism of the dam and the convective heat exchange component of the lower prism, with atmospheric air constitutes the critical factor in the formation of its thermal regime.

Under the influence of seasonal air temperature variations in the lower prism, there is an annual cycle of seasonal variations in the temperature of the rock fill, which follows the temperature of the outside air, lagging behind it in phase and amplitude. The magnitude of this lag depends upon the coordinates of a given point in the fill, and time. Maximum cooling of the lower prism occurs annually at the end of February and the beginning of March, while maximum heating occurs in August and September. The temperature of the lower prism changes from -12°C to -4°C during the year. The average annual temperature of the lower prism toward the end of construction matched the average annual ambient air temperature, and has continued to remain approximately the same during the eight years that the dam has been in operation.

When construction of the dam was complete, and while it was still operating at intermediate head levels,

three basic temperature zones appeared in the lower prism:

I. A lower zone, with negative temperature the year round;

II. An upper zone, whose temperature changes sign during the year;

III. A zone beneath the apron, which remains at positive temperatures the year round (Figure 2).

Since the dam has been in operation, temperature zones I and III have been seen to grow at the expense of a considerable shrinkage of zone II. Between 1969 and 1975, the relative area of zone I in a cross section of the river-bed portion of the dam increased from 60 to 65% and that of zone III grew from 6 to 12%, while zone II shrank from 34 to 23%.

The formation of the thermal regime of the dam is accompanied by a decrease in the rate of movement of the air in the lower prism, a drop in the amplitude of the seasonal variations in the temperature of the rock fill, and blockage of the pores in the fill by clay and ice.

Between 1969 and 1976 the rate of movement of the air in the lower prism fell by approximately a factor of 2. The decrease in the amplitude of seasonal variations in fill temperature in various parts of the lower prism is proceeding at different intensities. In the area adjacent to the surface of the lower slope, the amplitude of the seasonal variations in fill temperature decreased by a factor of 1.6 from 1969 to 1976; in the inner region of the lower prism it dropped by a factor of 3 to 3.3. The relative area of the region where the amplitude of fill temperature variations was less than 0.1 of the amplitude of the variations in the average decade temperature of the outside air, in the cross section of the river-bed part of the dam, increased from 12 to 68% from 1968 to 1975. However, the relative area of the region with an amplitude of seasonal fill temperature variations of greater than 0.4 of the amplitude of the variations in the average decade temperature of the outside air shrank from 17.3 to 9.6% (Figure 3).

Due to the considerable cooling action of the lower prism on the foundation of the dam, the water in the lower pool, which melts the lower prism to a height of 4.5 to

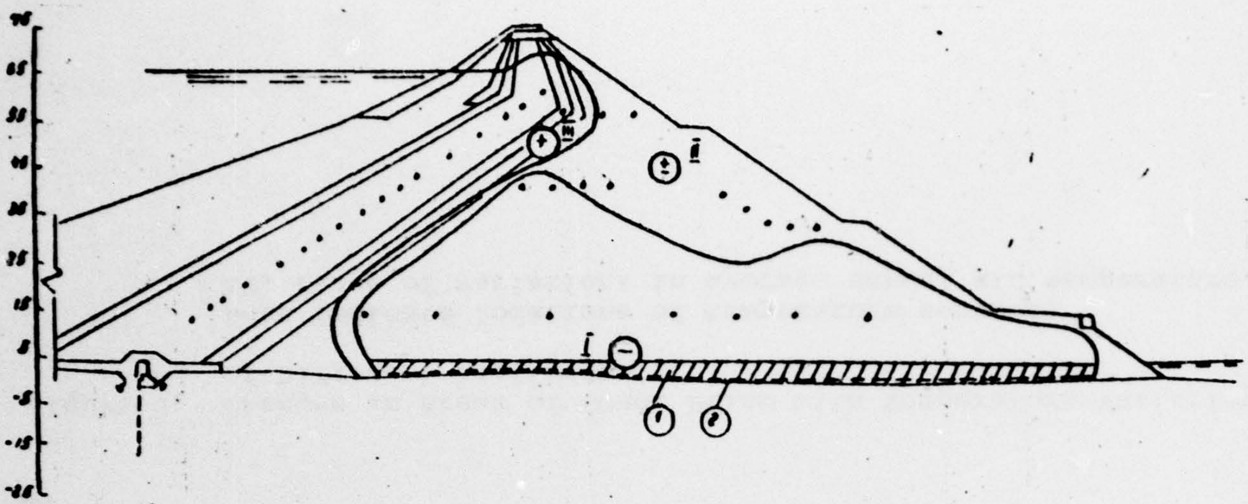

Figure 2. Basic Temperature Zones of Lower Prism in 1975.

I: Zone with negative year-round temperature;
II: Zone where temperature changes sign during the year;
III: Zone with positive year-round temperature;
1, layer of rock and ice;
2, concentrated filtration current;
the dots indicate locations of temperature sensors.

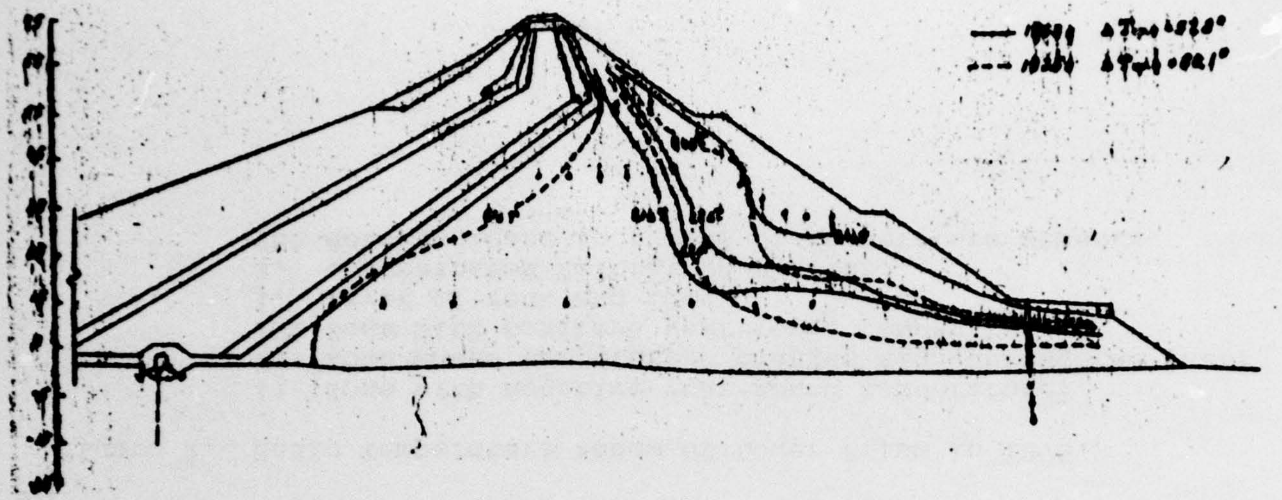

Figure 3. Changes in Areas of Lower Prism with Temperature Variations of Different Amplitudes.

Dots indicate locations of temperature sensors; ΔT, range of variations in average annual air temperature.

4.8 m, was frozen. In 1974, the average annual temperature of this layer of rock and ice in contact with the foundation in the vicinity of the lower berm in the branch of the dam was -14.5°C. Under the influence of negative temperatures like these, the talik beneath the river bed froze to a depth of 54 m (Figure 4).

The cooling effect of the lower prism upon the lower limit of the dam apron was small, even during construction.

During operation, the warming influence of the reservoir has been considerably greater than the cooling influence of the lower prism and the part of the rock fill below the apron, which had a year-round positive temperature that continues to increase.

Observation of the thawing of the bed and banks of the reservoir showed that the reservoir had practically no warming effect on the frozen rocks of the shore above the water line at the mean backwater level. The depth of thawing of the slopes along the banks of the reservoir, which were always lower than the water level, amounted to 9 to 11 m during the period from 1969 to 1975, while the depth of the zone of thermal influence of the reservoir upon the permafrost soil (with a temperature of -4°C at the end of 1975) was more than 50 meters.

The process of thawing of the foundation beneath the upper wedge of the dam was complex, governed by the important difference in degree of fissuring and degree of freezing of the rocks on the left and right banks of the dam. The thawing rate of the foundation at the left bank abutment of the dam during the first years of operation reached 5 - 8 m per year, while at the right-bank abutment it was 2.5 m annually. In the river-bed part of the dam, near the interface with the natural talik beneath the river bed (in other words, in the area of the most carefully preserved and monolithic diabase) the average annual thawing rate of the foundation decreased from 2.5 to 1.1 meters amnually from 1969 to 1974.

The principal result of analysis of the results of field observations of the thermal regime of the Vilyuysk power station dam is that no lower limit can be maintained for the apron of a high-head earth-rock dam in the frozen state, due to natural air convection in the pores of the rock fill in the lower prism of the dam.

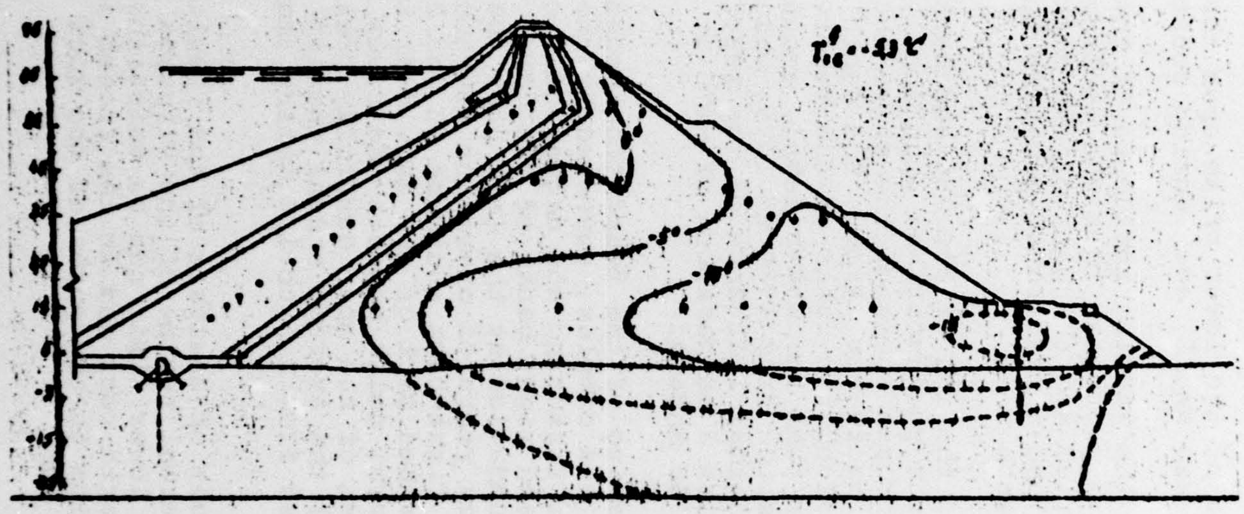

Figure 4. Temperature Conditions in Dam: 1975 (Averages for the year).

Dots indicate locations of temperature sensors;
T [illegible], average annual air temperature.